(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
5 June 2003 (05.06.2003)

PCT

(10) International Publication Number
WO 03/046835 A1

(51) International Patent Classification[7]: G06T 11/00

(21) International Application Number: PCT/US02/37159

(22) International Filing Date:
19 November 2002 (19.11.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/990,521 21 November 2001 (21.11.2001) US

(71) Applicants: **KONINKLIJKE PHILIPS ELECTRONICS NV** [NL/NL]; Groenewoudseweg 1, NL-5621 BA Eindhoven (NL). **PHILIPS MEDICAL SYSTEMS (CLEVELAND), inc.** [US/US]; 595 Miner Road, Cleveland, OH 44143 (US).

(72) Inventors: **SUBRAMANYAN, Krishna**; 7305 Popham Place, Solon, OH 44139 (US). **CHANDRA, Shalabh**; 6550 Maplewood Drive, Apt. #203, Mayfield Heights, OH 44124 (US).

(74) Agents: **LUNDIN, Thomas, M.** et al.; Philips Medical Systems (Cleveland), Inc., 595 Miner Road, Cleveland, OH 44143 (US).

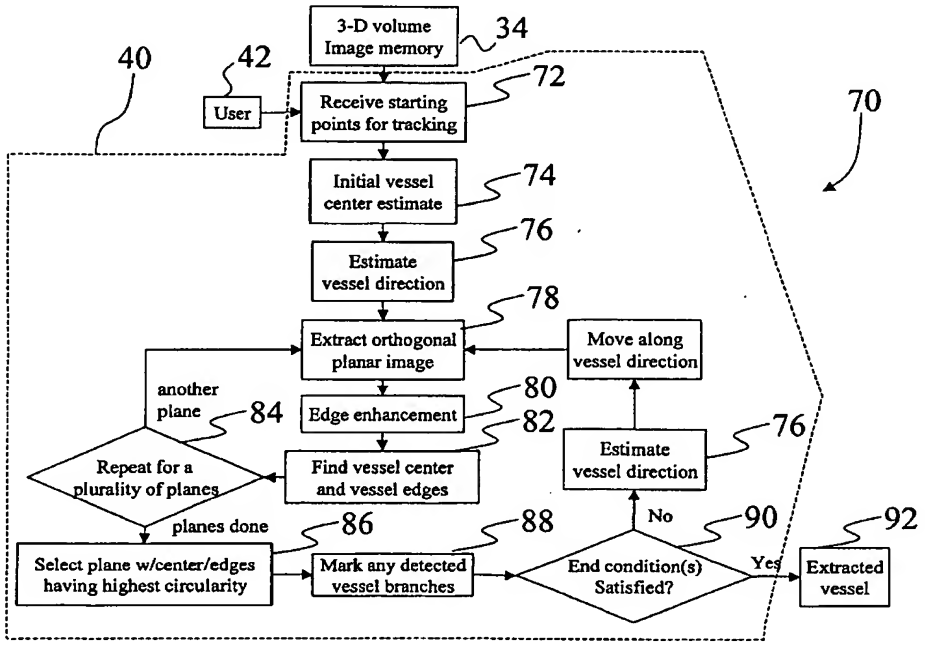
(81) Designated States *(national)*: IL, JP.

(84) Designated States *(regional)*: European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR).

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: VESSEL TRACKING AND TREE EXTRACTION METHOD AND APPARATUS



(57) Abstract: Computed tomography (CT) data (28) is collected for a plurality of slices by a CT scanner (10). At least a portion of the CT data is reconstructed (32) to form a volume image (34) defined by a plurality of two-dimensional image slices. At least one starting point is identified (72) within a blood vessel imaged in the three-dimensional image volume (34). The blood vessel is recursively tracked (70) to form a blood vessel representation (92).

WO 03/046835 A1

VESSEL TRACKING AND TREE EXTRACTION METHOD AND APPARATUS

The present invention relates to the medical imaging arts. It particularly relates to the imaging and interpretation vascular structures imaged in three-dimensional medical images, such as multi-slice or spiral computed tomography (CT) images, and will be described with particular reference thereto. However, the invention will also find application in conjunction with other imaging techniques such as magnetic resonance-based imaging (MRI) or nuclear medicine, as well as in interpretation of other tortuous and/or furcating tubular structures having constant or variable diameters.

Based upon current and future trends in CT technology, cardiac imaging, and in particular coronary artery imaging, is an increasingly important application in which CT is expected to play a significant role. Coronary arteries supply blood feeding the heart muscle. Failure of a coronary artery can produces myocardial infarction leading to chronic heart problems and/or catastrophic heart attacks, which are a leading cause of death in the United States today.

On the data acquisition side, development of multi-slice CT systems having increasingly improved resolution particularly in the slice-direction are making clinical CT imaging of vascular systems attractive. However, for CT to gain greater clinical acceptance in this area, reconstruction and post-processing of the images at selected phase(s) of the cardiac cycle should be automated to the greatest extent possible. Currently, coronary artery tracking in multi-slice CT data is a cumbersome and laborious task. Prior art vessel tracking systems are typically not directed toward CT data, which has peculiar issues such as high noise levels when compared with techniques such as magnetic resonance imaging (MRI). Past vessel tracking systems which are directed toward multi-slice CT are limited by long computation times.

The present invention contemplates an improved vessel tracking method and apparatus which overcomes the aforementioned limitations and others.

According to one aspect of the invention, a medical imaging method is provided. Computed tomography (CT) imaging data is collected. At least a portion of the CT imaging data is reconstructed to form a volume image representation. At least one starting point is identified within a blood vessel imaged in the volume image representation. The blood vessel is recursively tracked from the starting point to form a blood vessel representation.

According to another aspect of the invention, an apparatus is disclosed for medical imaging. An imaging means is provided for collecting computed tomography (CT) imaging data. A reconstruction means is provided for reconstructing at least a portion of the CT imaging data to form a volume image representation. A means is provided for identifying at least one starting point within a blood vessel imaged in the volume image representation. A tracking means is provided for recursively tracking the blood vessel from the starting point to form a blood vessel representation.

One advantage of the present invention is that it provides a direct approach for extracting the vessel centerline in multi-slice CT data.

Another advantage of the present invention is that it automatically extracts the vessel boundaries to provide accurate lumen information in the tracked vasculature.

Another advantage of the present invention is that it detects vessel branches. This facilitates generation of the vascular tree structure by successive applications of the vessel tracking.

Yet another advantage of the present invention is that it assesses the optimal phase in retrospective cardiac gating.

Numerous additional advantages and benefits of the present invention will become apparent to those of ordinary skill in the art upon reading the following detailed description of the preferred embodiments.

The invention may take form in various components and

arrangements of components, and in various steps and arrangements of steps. The drawings are only for the purpose of illustrating preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 schematically shows an exemplary multiple-slice CT imaging system that suitably practices an embodiment of the invention;

FIGURES 2 schematically shows an exemplary method implemented by the vessel tracker of FIGURE 1;

FIGURES 3 shows an exemplary embodiment of the vessel center and edges processor;

FIGURE 4 shows an exemplary distribution of rays for use in conjunction with the constructing the central measure map;

FIGURE 5 shows an exemplary central measure map;

FIGURE 5A show in inset form the image slice corresponding to the central measure map of FIGURE 5;

FIGURE 6 shows an exemplary three-dimensional rendering of a vessel tracked in accordance with the method of FIGURE 2; and

FIGURE 7 schematically shows another embodiment wherein the tracking system is used to optimize the retrospective gating phase.

With reference to FIGURE 1, a multiple-slice computed tomography (CT) scanner **10** includes a patient support **12** such as a patient bed which is linearly movable inside an examination region **14**. An x-ray tube assembly **16** mounted on a rotating gantry projects a cone beam or a plurality of parallel fan beams of radiation through the examination region **14**. A collimator **18** collimates the radiation beam or beams in two dimensions. In third generation scanners, a two-dimensional x-ray detector **20** is disposed on the rotating gantry across the examination region from the x-ray tube. In fourth generation scanners, an array of two-dimensional detector rings **22** is mounted on a stationary gantry around the rotating gantry.

Whether third or fourth generation, the x-ray

detectors **20**, **22** operate in known ways to convert x-rays that have traversed the examination region **14** into electrical signals indicative of x-ray absorption between the x-ray tube **16** and the detectors **20**, **22**. An electrocardiogram **24** monitors phases of a cardiac cycle of a patient **26**. The x-ray absorption signals, along with information on the angular position of the rotating gantry and the cardiac phase, are communicated to a data memory **28**.

An acquisition controller **30** communicates **32** with the CT scanner **10** to control CT scanning of a patient **26**. The data corresponding to an operator-selected cardiac phase is reconstructed by a reconstruction processor **32** which reconstructs the selected cardiac phase x-ray absorption data into a plurality of CT image slices stored in a CT volume image memory **34**. The reconstruction processor **32** operates using the filtered back-projection technique known to the art or using other reconstruction techniques.

In another suitable embodiment (not shown), the patient couch advances continuously such that the data acquisition occurs over a spiral geometry. The resulting spiral data is reconstructed into a three-dimensional image again stored in image memory **34**. Those skilled in the art will also recognize that the invention is not limited to CT, but is also applicable to magnetic resonance imaging (MRI) and other methods capable of three-dimensionally imaging tubular biological structures.

For coronary artery imaging, the x-ray absorption data are advantageously sorted by cardiac cycle phase so that the slices do not encounter registration errors across image slices or motion artifacts within the slices due to the motion of the heart. Additionally, in order to emphasize the vasculature, a contrast agent **36**, such as an iodine-based contrast agent, is administered to the patient **26**.

A vessel tracker **40** advantageously selectively tracks coronary arteries based on starting points supplied by an

associated user **42** through a user interface **44**, which is preferably interactive. As the vessel tracker tracks the vessels, key vessel-defining characteristics such as the vessel center and periphery information are stored in a vessel tree memory **46**. A three-dimensional surface rendering processor **48** generates a 3-D representation, optionally rotatable, of the tracked vessel tree. The user interface **44** also permits selective viewing of the contents of the three-dimensional volume image memory **34**, the output of the tracker **40**, and the 3-D rendering. Further, the user interface **44** allows the user **42** to communicate with and direct the data acquisition controller **30** so that the user **42** can operate the CT scanner **10**.

The apparatus embodiment of FIGURE 1 is exemplary only. Those skilled in the art will be able to make modifications to suit particular applications. For example, the user interface **44** can include other components, such as printers, network connections, storage units, and the like (not shown), to facilitate efficient manipulating of the CT scanner **10**. In another embodiment, the user interface **44** is a computer and vessel tracker **40** is a software component residing thereon.

With continuing reference to FIGURE 1 and with further reference to FIGURE 2, an exemplary vessel tracking method **70** embodiment is described. The user **42** is interrogated via the user interface **44** and supplies one or more starting points or landmarks **72** within the three-dimensional volume image memory **34**. One of the starting points **72** serve as an initial vessel center estimate **74**.

A vessel direction is estimated **76** by extrapolating from at least two vessel center points. The vessel center points are supplied recursively, i.e. corresponding to previously identified vessel centers. To initiate the tracking direction, the starting points **72** can be used. In one embodiment, at least three points are used to extrapolate by

fitting the points to a spline curve or other suitable curved linear function. In another embodiment, two points are taken at a time and the centerline is tracked between them. To avoid erroneously following a sharp turn corresponding to a branch, an end point is also supplied to indicate the principle vessel direction. Another method for avoiding inadvertently following branches is to weight the points used to bias against sharp curving. In yet another suitable embodiment, the vessel direction is obtained by line filtering a finite volume, extracting an inertia matrix, and performing an Eigen analysis of the inertia matrix to yield a vessel direction.

With continuing reference to FIGURES 1 and 2, a normal planar image that is orthogonal to the vessel direction is extracted **78** from the 3-D volume image of memory **34**. The size of this plane can be varied based on the size of the vessel being tracked, but in any event it should be at least large enough to contain the entire vessel cross-section. The appropriate orthogonal plane is identified by transforming a plane parallel to the x-y plane into the orthogonal orientation according to:

$$\gamma = \arctan\left(\frac{n_y}{n_x}\right) \quad , \quad \phi = \arctan\left(\frac{n_z}{\sqrt{n_x^2 + n_y^2}}\right) \qquad (1)$$

where (n_x, n_y, n_z) is the directional normal along the vessel direction **76**, γ is the angle of the plane with respect to the z-axis, and φ is the angle of the plane with respect to the y-axis. The transformed coordinates are used to tri-linearly interpolate the image voxels from the 3-D volume image **34**.

With the orthogonal plane found, the vessel center and the vessel boundaries are identified within the plane **78**. Boundary identification is complicated by the low signal-to-noise ratio typically associated with multi-slice CT image data. To improve the boundaries' detectability, an edge enhancement **80** is preferably performed. In one embodiment, a

Gaussian function convolutional smoothing is applied prior to computing directional component magnitudes to determine the presence of edges. Optionally, these edges can be superimposed onto the image in the display portion of the user interface **44** and the user **42** prompted to visually verify the edge identification. The edge enhancement just described is exemplary only, and other edge enhancement algorithms known to the art can instead be employed.

The edge enhanced planar image **80** is analyzed to find the vessel center and boundaries **82**. In an exemplary embodiment, a central measure map is used for this analysis, as will be described in more detail later.

Those skilled in the art will recognize that the accuracy of the vessel centers and boundaries estimation **82** will depend upon the orthogonality of the planar image **80** relative to the actual vessel direction. Since the vessel direction **76** is only an estimate, in one preferred embodiment the vessel plane extraction **78**, edge enhancement **80**, and vessel center/edges analysis **82** are repeated **84** for a small plurality of planes at several tilts about the estimated vessel direction **76**. For example, five planes are analyzed, one exactly orthogonal to the estimated direction **76**, two other planes with tilts of $\pm\theta$ degrees about a selected relative ``x'' axis, and two additional planes with tilts of $\pm\theta$ degrees about the corresponding orthogonal ``y'' axis. Since for an ideal cylindrical vessel the orthogonal plane will have vessel boundaries which is perfectly circular, that orthogonal plane of the small plurality of planes which has the most circular vessel boundary is selected **86**.

In the course of the center and boundaries analysis **82**, vessel branching may be detected. If so, vessel branches are advantageously marked **88** for possible later tracking. In this way, the tracker can be applied recursively to track an entire branched vascular tree.

Once the vessel center and boundaries are found, the process recursively iterates until a termination condition is satisfied **90**. Suitable termination conditions optionally include, but are not limited to, actual termination of the vessel in the image, narrowing of the vessel below a pre-selected diameter, and an end point identified from among the starting points **72**. The end result of the recursive method is the extracted vessel **92**.

With continuing reference to FIGURE 2 and with further reference to FIGURE 3, a suitable embodiment of the vessel center and edge analysis is described. The analysis is performed in the edge enhanced planar image **100** output by the edge enhancement processor **80**. A central measure map is computed as follows.

With reference to FIGURE 3 and with further reference to FIGURE 4, for a pixel (i,j) **102**, a plurality of rays are generated **104** which pass through the point (i,j) **102** at a selected angular separation α **106** so that there are n **108** rays generated. In the exemplary FIGURE 4 where $\alpha = 30°$, there are n=6 rays indexed by k which radially span about the point (i,j) **102**.

For each ray, the gradient is computed **110** by convolving with a gaussian derivative kernel according to:

$$\nabla R(\vec{r},\sigma) = I(\vec{r}) * \sigma^{\gamma} \nabla G(x,\sigma) \qquad (2)$$

where

$\vec{r}$ = *ray,* $I(\vec{r})$ = *image array, and*

$\sigma^{\gamma} \nabla G(x,\sigma)$ = *the gaussian derivative kernel*

where σ is the gaussian variance which serves as a scale factor **112** in the method and is selected based on the size or diameter

of the vessel being tracked. Those skilled in the art will recognize that for larger scale factors only the dominant edges will be present after the gradient transform. The factor γ in equation (2) is a normalizing factor corresponding to Lindeberg's power constant which preserves the image characteristics across the gradient transform. $G(x,\sigma)$ is the well known Gaussian function given by:

$$G(x,\sigma)=\frac{1}{2\pi\sigma^2}e^{\frac{-x^2}{2\sigma^2}} \qquad (3)$$

and the derivative of the gaussian, defined as:

$$\nabla G(x,\sigma)=\frac{\partial}{\partial x}G(x,\sigma) \qquad (4)$$

is computed using a three-point difference operation, i.e. convolving with a {1, 0, -1} kernel.

A gradient magnitude is calculated **114** along the radial direction according to:

$$\frac{\partial R_{1,2}}{\partial \vec{r}_{1,2}}=\left(\frac{|\nabla R(\vec{r},\sigma)|}{|\vec{r}|}\right)_{\vec{r}_{1,2}=\text{first maximums}} \qquad (5)$$

where the subscripts 1,2 refer to the positive and negative directions along the linear image array I(r) and the magnitude of the vector r reaches to the first maximum in the transformed radial array. The central measure map is then generated **116** by transforming each pixel (i,j) **102** according to the transformation:

$$CMQ(i,j) = \frac{1}{n}\sum_{k=1}^{n}\left(\frac{\min\left\{\frac{\partial R_1}{\partial \vec{r}_k}, \frac{\partial R_2}{\partial \vec{r}_k}\right\}}{\max\left\{\frac{\partial R_1}{\partial \vec{r}_k}, \frac{\partial R_2}{\partial \vec{r}_k}\right\}}\right) \qquad (6)$$

The CMQ function is indicative of how well centered the point (i,j) is within its surrounding edge boundaries. The calculation of CMQ(i,j) is repeated **118** for each pixel (i,j) **102** to produce the central measure map **120**. The vessel center is selected **122** as the point (i,j) having the largest central measure map value CMQ(i,j). Generally, the vessel center will have CMQ close to 1.0 for circular and elliptical borders, with decreases therefrom as vessel edge irregularities increase. With the center selected **122**, the edge points are selected **124** as the $r_{1,2}$ vectors of equation (5), and a circularity is estimated therefrom since for perfect circularity the $r_{1,2}$ vectors are all equal at the vessel center.

With reference to FIGURE 5, an exemplary central measure map **140** is shown, along with an inset FIGURE 5A of the corresponding image slice **142**. The vessel center **144** is identified as the largest value of the central measure map. Additional peaks **146** are also seen in the central measure map, and these correspond to smaller nearby vessels which are also discernable in the inset image slice **142**. Those skilled in the art will recognize that at a vessel branch there will be a merging of the central measure map peaks of the main vessel and the smaller branch coming off. Such a merging can be detected to facilitate marking of branches **88** (FIGURE 2). The tracking system **70** can then be successively applied to each marked branch to recursively track the full vascular tree.

With reference to FIGURE 6, an exemplary three-dimensional rendering of a tracked vessel **160** is shown, rendered by a centerline **162** formed in three dimensions by connecting the identified vessel center of each orthogonal plane, and by a plurality of two dimensional vessel edge

contours **164** situated in three dimensional space which correspond to the vessel boundaries of the plurality of orthogonal planes. A sharp bend **166** in the vessel was properly tracked, and a widened structure **168**, which could be an aneurysm, vessel branch point, or the like, is also detected. Of course, the tracked vessel can also be rendered using other methods, such as a shaded three-dimensional representation, a projection, or the like.

With reference returning to FIGURE 1 and with further reference to FIGURE 7, another application of the present invention is described, wherein the tracking provides a method for determining optimal phasing in retrospective CT gating. The electrocardiograph **50** (FIGURE 1) records an electrocardiogram **ECG** as shown schematically in FIGURE 7. A first cardiac cycle CC_1 is shown in full, with several conventionally recognized points in the electrocardiogram **ECG** labeled: namely the atrial depolarization **P**, ventricular depolarization **Q**, **R**, **S**, and ventricular repolarization **T**. A second cardiac cycle CC_2 with points **P'**, **Q'**, **R'**, **S'**, **T'** labeled is shown in part. The phasing of the retrospective CT gating is indicated as **G**. As indicated below the **ECG**, multi-slice CT data acquisition occurs continuously during the cardiac cycling. After acquisition, the CT data is analyzed using retrospective gating which employs the phasing **G** as a temporal reference by which data acquired across cardiac cycles is synchronized. For a non-optimal phase **G** selection, the tracking is less effective and often even fails completely. Thus, by performing tracking for a range of phases **G** of the retrospective gating, the optimal phase is selected based on the success and quality of the vessel tracking.

Claims

1. A medical imaging method comprising:

collecting computed tomography (CT) (10) imaging data;

reconstructing (32) at least a portion of the CT imaging data to form a volume image representation (34);

identifying (72) at least one starting point (74) within a blood vessel imaged in the volume image representation (34); and

recursively tracking (70) the blood vessel from the starting point (74) to form a blood vessel representation (92).

2. The method as set forth in claim 1, wherein the recursive tracking (70) includes:

estimating (76) a vessel direction in a vicinity of the starting point (74);

extracting (78) a planar image containing the vessel center (74) from the three-dimensional image (34), which planar image is perpendicular to the estimated vessel direction;

edge-enhancing (80) the planar image;

locating (82) a vessel center (144) in the planar image;

finding (82) vessel boundaries (164) in the planar image;

extrapolating a new estimated (76) vessel center along the vessel direction; and

recursively repeating (90) the estimating (76), extracting (78), edge-enhancing (80), locating (82), finding (82), and extrapolating steps to track the vessel.

3. The method as set forth in claim 2, wherein the locating (82) of a vessel center (144) in the planar image includes:

computing (102, 104, 110, 114, 116, 118) a central measure

function (120, 140); and

selecting (122) the vessel center (144) as a pixel of the planar image having a maximum central measure function.

4. The method as set forth in claim 3, wherein the computing (102, 104, 110, 114, 116, 118) of a central measure function (120, 140) includes:

extracting (104) a plurality of linear arrays of interpolated pixels which intersect a selected pixel;

transforming (110) the linear arrays by convolving with a gaussian derivative (112);

identifying (114) first maximum values in positive and negative directions along the linear arrays;

calculating (116) a merit function based on the transformed linear arrays which is indicative of how well centered the point (i,j) is within its surrounding edge boundaries; and

repeating (118) the extracting (104), transforming (110), and calculating (116) for a plurality of selected pixels.

5. The method as set forth in claim 4, wherein the finding (82) of vessel boundaries (164) in the planar image includes:

identifying (124) vessel boundaries as the first maximum values for the selected (122) vessel center.

6. The method as set forth in any one of claims 2-5, wherein the finding (82) of vessel boundaries (164) in the planar image includes:

extracting (104) a plurality of linear arrays of interpolated pixels which intersect the vessel center; and

identifying (124) vessel edges in positive and negative directions along each linear array.

7. The method as set forth in any one of claims 2-6, wherein the estimating (76) of a vessel direction includes:

fitting a curve to a plurality of previous vessel centers.

8. The method as set forth in any one of claims 2-6, wherein the estimating (76) of a vessel direction includes:

fitting a curve to a plurality of previous vessel centers which are weighted to bias against sharp curving.

9. The method as set forth in any one of claims 2-6, wherein the estimating (76) of a vessel direction includes:

line filtering the finite volume;

extracting an inertia matrix from the filtered volume; and

performing an Eigen analysis of the inertia matrix to estimate a vessel direction.

10. The method as set forth in any one of claims 2-9, further including:

during the finding (82) of a vessel center (144) and vessel boundaries (164), marking (88) vessel boundaries indicative of vessel branching;

recursively repeating the vessel tracking (70) at each marked (88) vessel boundary to track vessel branches; and

combining the blood vessel representation (92) and the tracked vessel branches to form a vessel tree.

11. The method as set forth in any one of claims 2-10, wherein the step of extracting (78) a planar image includes extracting (78) a plurality of planar images deviating from perpendicular to the estimated vessel direction by selected small-angle tilts, the method further including:

repeating (84) the steps of edge-enhancing (80) the planar image, locating (82) a vessel center (144) and vessel

boundaries (164) for each of the plurality of planar images;

selecting (86) the vessel boundaries having the highest circularity from among the vessel boundaries of the plurality of planar images; and

selecting (86) the vessel center corresponding to the selected vessel boundaries.

12. The method as set forth in any one of claims 1-11, wherein the CT (10) imaging data is collected over a plurality of cardiac phases (P, Q, R, S, T), the method further including:

retrospectively gating (G) to select the portion of CT imaging data corresponding to a selected cardiac phase for the reconstructing.

13. The method as set forth in any one of claims 1-12, further including:

selecting portions of the CT data using retrospective gating (G) corresponding to a range of the cardiac phases (P, Q, R, S, T); and

selecting an optimal cardiac phase based on the recursive tracking.

14. An apparatus for medical imaging, the apparatus comprising:

an imaging means (10) for collecting computed tomography (CT) imaging data;

a reconstruction means (32) for reconstructing at least a portion of the CT imaging data to form a volume image representation (34); and

a tracking means (40) for recursively tracking (70) a blood vessel from a selected starting point (74) within the blood vessel to form a blood vessel representation (92).

15. The apparatus as set forth in claim 14, wherein the tracking means (40) includes:

a means for estimating (76) a vessel direction in a vicinity of the starting point (74);

a means for extracting (78) a planar image containing the vessel center (74) from the three-dimensional image (34), which planar image is perpendicular to the estimated vessel direction;

a means for edge-enhancing (80) the planar image;

a means for locating (82) a vessel center (144) in the planar image;

a means for finding (82) vessel boundaries (164) in the planar image;

a means for extrapolating a new estimated (76) vessel center along the vessel direction; and

a means for recursively invoking (90) the estimating (76), extracting (78), edge-enhancing (80), locating (82), finding (82), and extrapolating means to track the vessel.

16. The apparatus as set forth in claim 15, wherein the means for locating (82) a vessel center (144) includes:

a means for computing (102, 104, 110, 114, 116, 118) a central measure function (120, 140); and

a means for selecting (122) the vessel center (144) as a pixel of the planar image having a maximum central measure function.

17. The apparatus as set forth in either one of claim 15 and claim 16, wherein the means for finding (82) vessel boundaries (164) includes:

a means for extracting (104) a plurality of linear arrays of interpolated pixels which intersect the vessel center; and

a means for identifying (124) vessel edges in positive and

negative directions along each linear array.

18. The apparatus as set forth in any one of claims 15-17, wherein the means for estimating (76) a vessel direction includes:

a curve-fitting means for fitting a curve to a plurality of previous vessel centers which are weighted to bias against sharp curving.

19. The apparatus as set forth in any one of claims 15-18, wherein the means for extracting (78) a planar image extracts (78) a plurality of planar images deviating from perpendicular to the estimated vessel direction by selected small-angle tilts, the apparatus further including:

a means for repeatedly invoking (84) the edge-enhancing means (80) and the means (82) for locating a vessel center and vessel boundaries for each of the plurality of planar images;

a means for selecting (86) the vessel boundaries (164) having the highest circularity from among the vessel boundaries of the plurality of planar images; and

a means for selecting (86) the vessel center (144) corresponding to the selected vessel boundaries (164).

20. The apparatus as set forth in any one of claims 14-19, wherein the imaging means (10) collects imaging data over a plurality of cardiac cycles (CC_1, CC_2), the apparatus further including:

a cardiac gating means (24) for retrospectively gating (G) to select the portion of CT imaging data corresponding to a selected cardiac phase for reconstructing by the reconstuction means (32).

21. The apparatus as set forth in claim 20, wherein the cardiac gating means (24) includes:

an electrocardiograph (24).

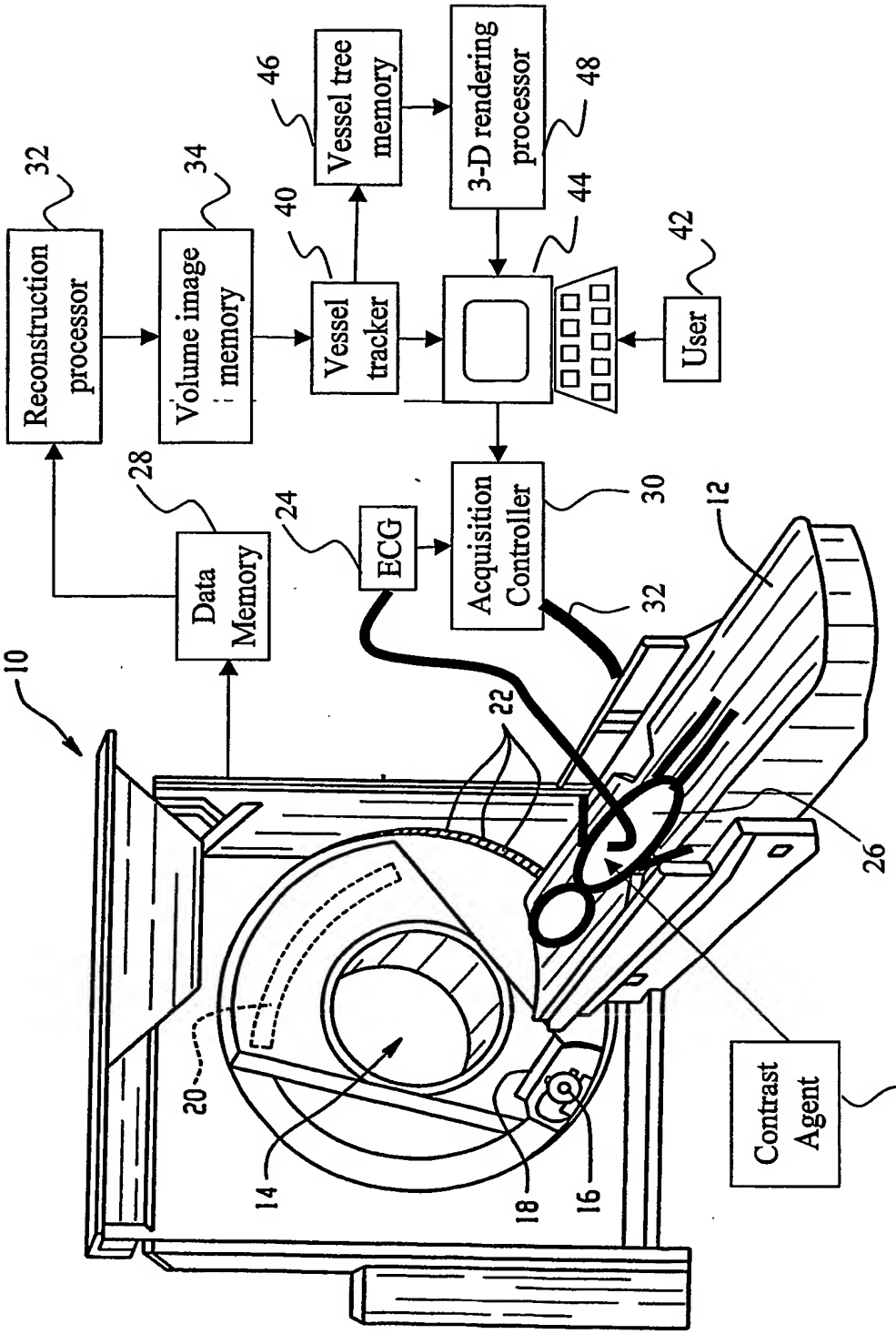
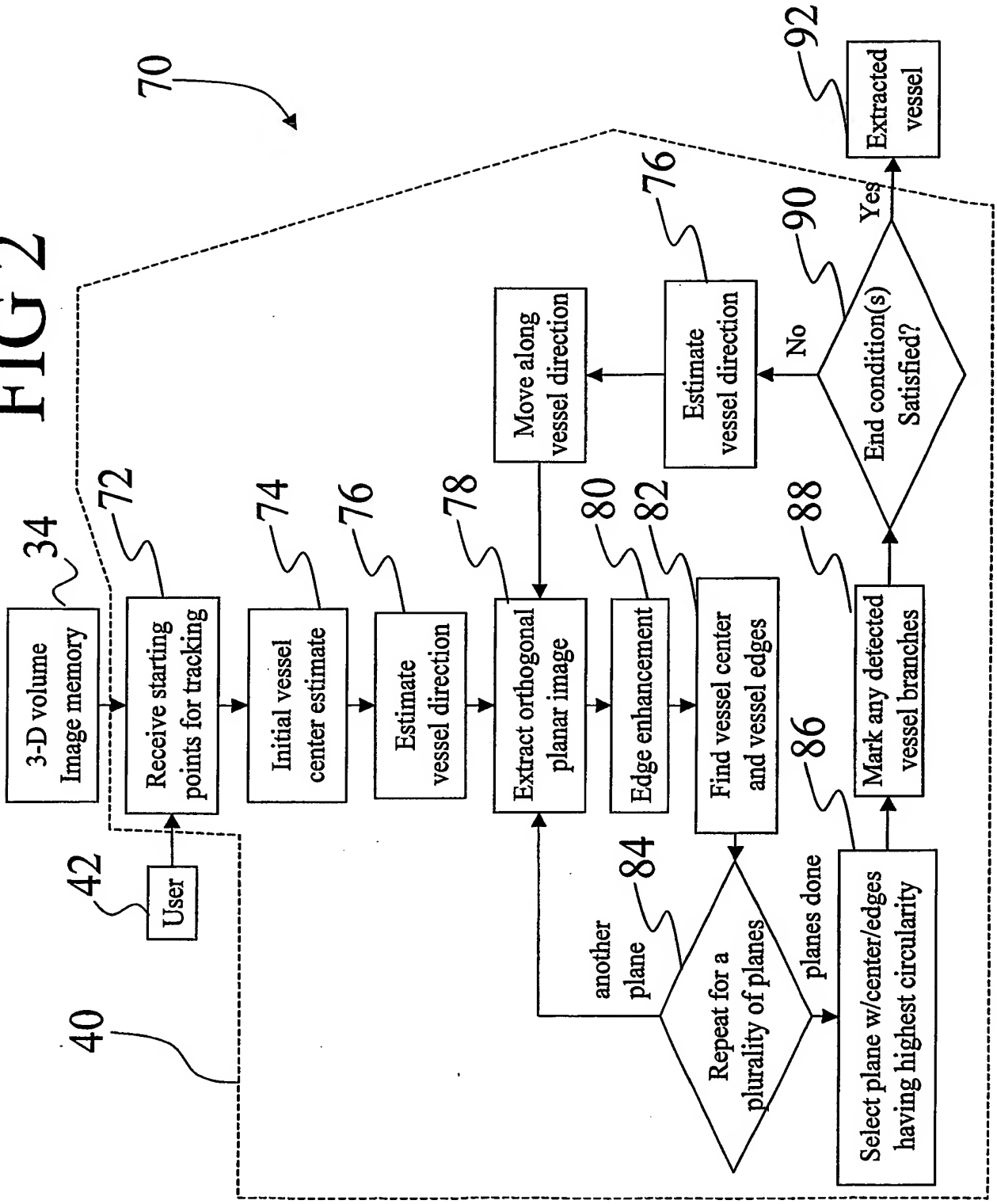

Reconstruction processor
32
Volume image memory
34
Vessel tracker
40
Vessel tree memory
46
3-D rendering processor
48
44
User
42
Data Memory
28
ECG
24
Acquisition Controller
30
12
10
32
22
26
Contrast Agent
36
20
14
18
16

FIG 1

FIG 2


70
92
Extracted vessel
Yes
90
End condition(s) Satisfied?
No
76
Estimate vessel direction
Move along vessel direction
34
3-D volume Image memory
72
Receive starting points for tracking
74
Initial vessel center estimate
76
Estimate vessel direction
78
Extract orthogonal planar image
80
Edge enhancement
82
Find vessel center and vessel edges
88
Mark any detected vessel branches
86
Select plane w/center/edges having highest circularity
84
Repeat for a plurality of planes
another plane
planes done
42
User
40

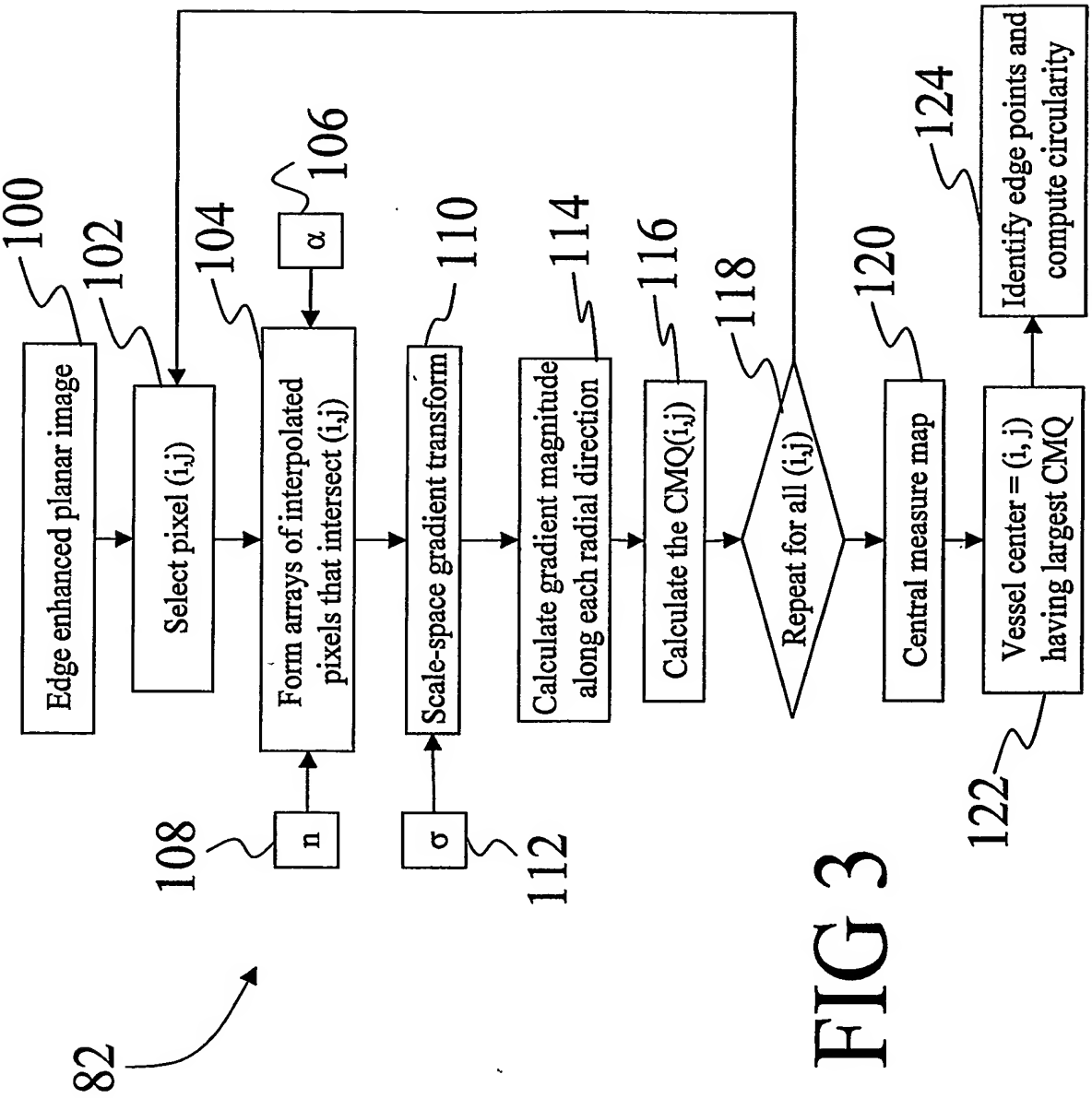

Edge enhanced planar image
Select pixel (i,j)
Form arrays of interpolated pixels that intersect (i,j)
Scale-space gradient transform
Calculate gradient magnitude along each radial direction
Calculate the CMQ(i,j)
Repeat for all (i,j)
Central measure map
Vessel center = (i, j) having largest CMQ
Identify edge points and compute circularity
α
n
σ
100
102
104
106
108
110
112
114
116
118
120
122
124
82

FIG 3

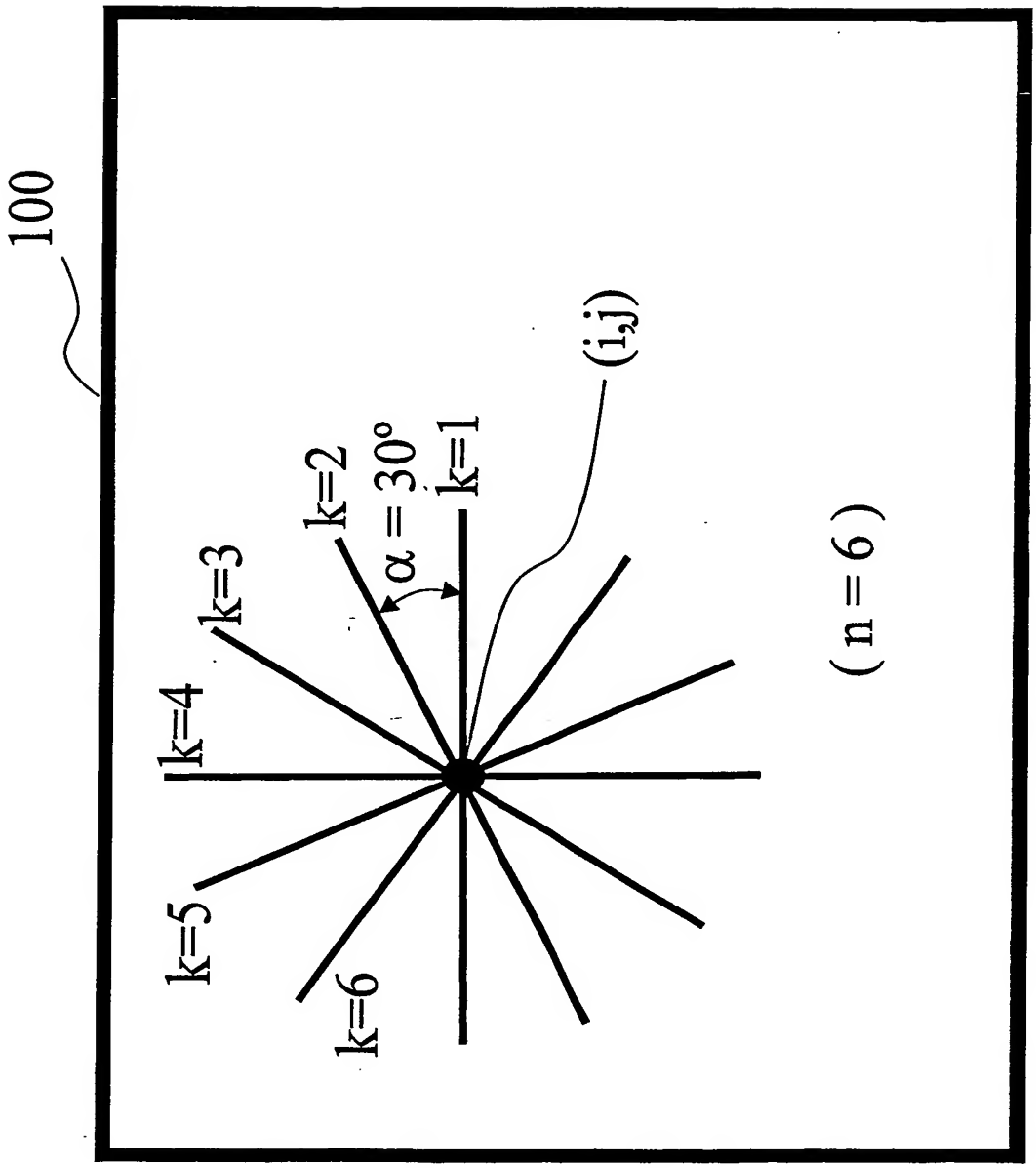


FIG 4

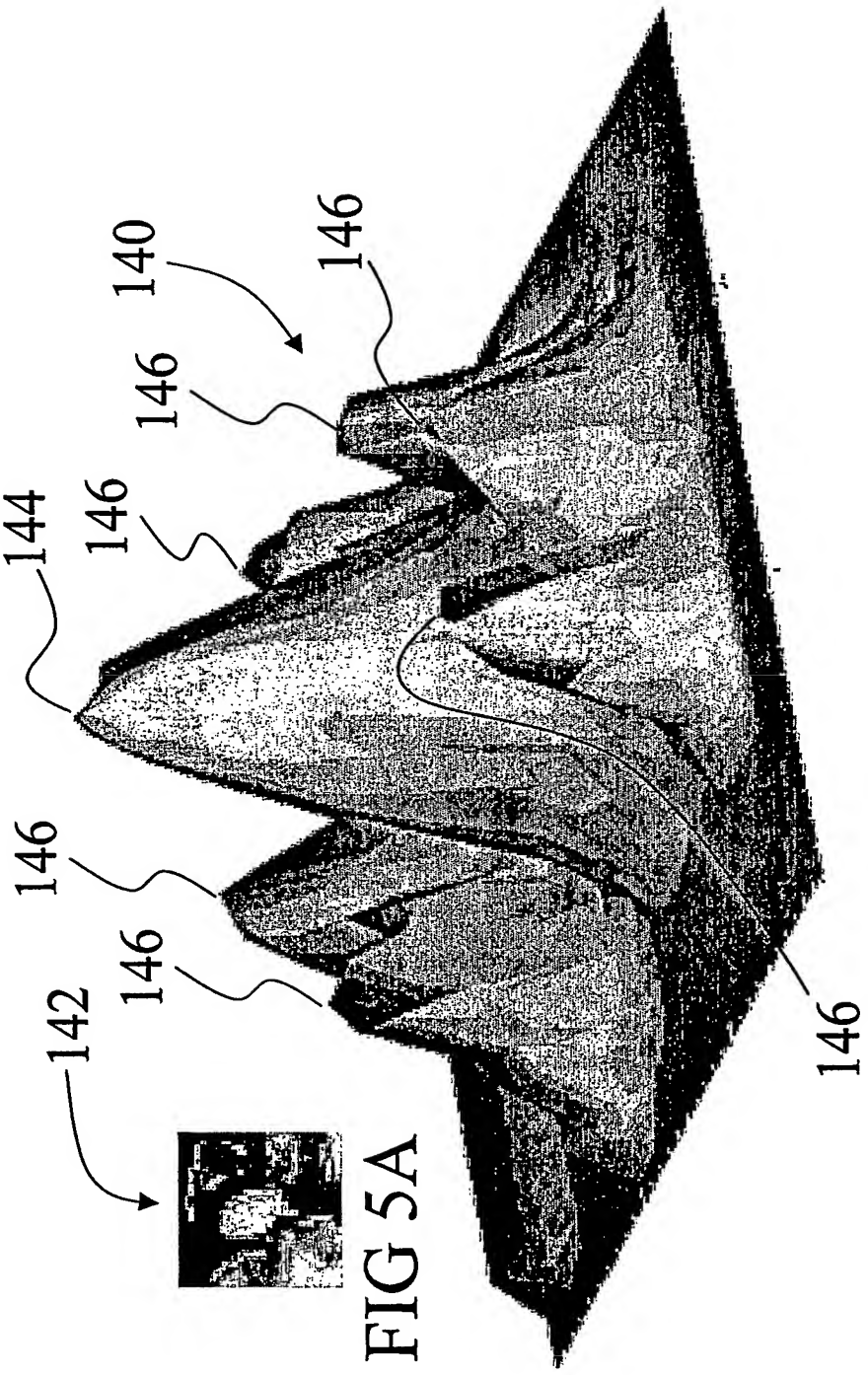


FIG 5

FIG 5A

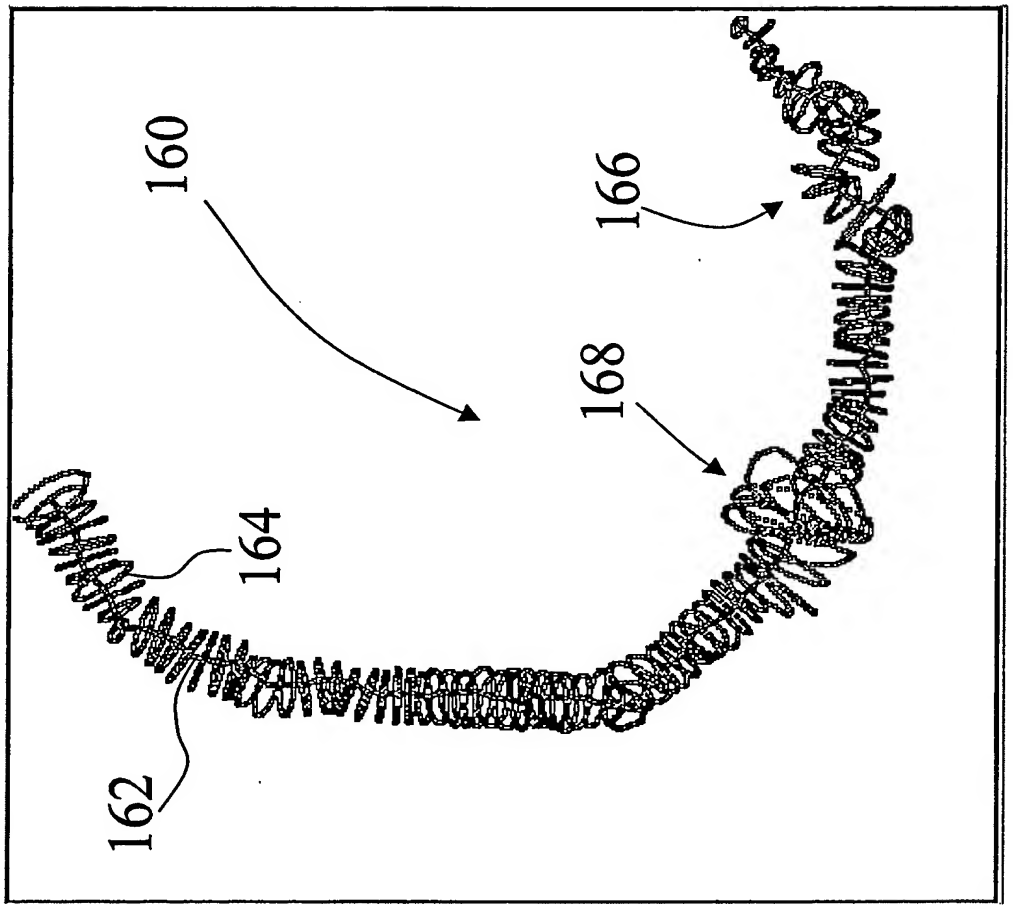


FIG 6

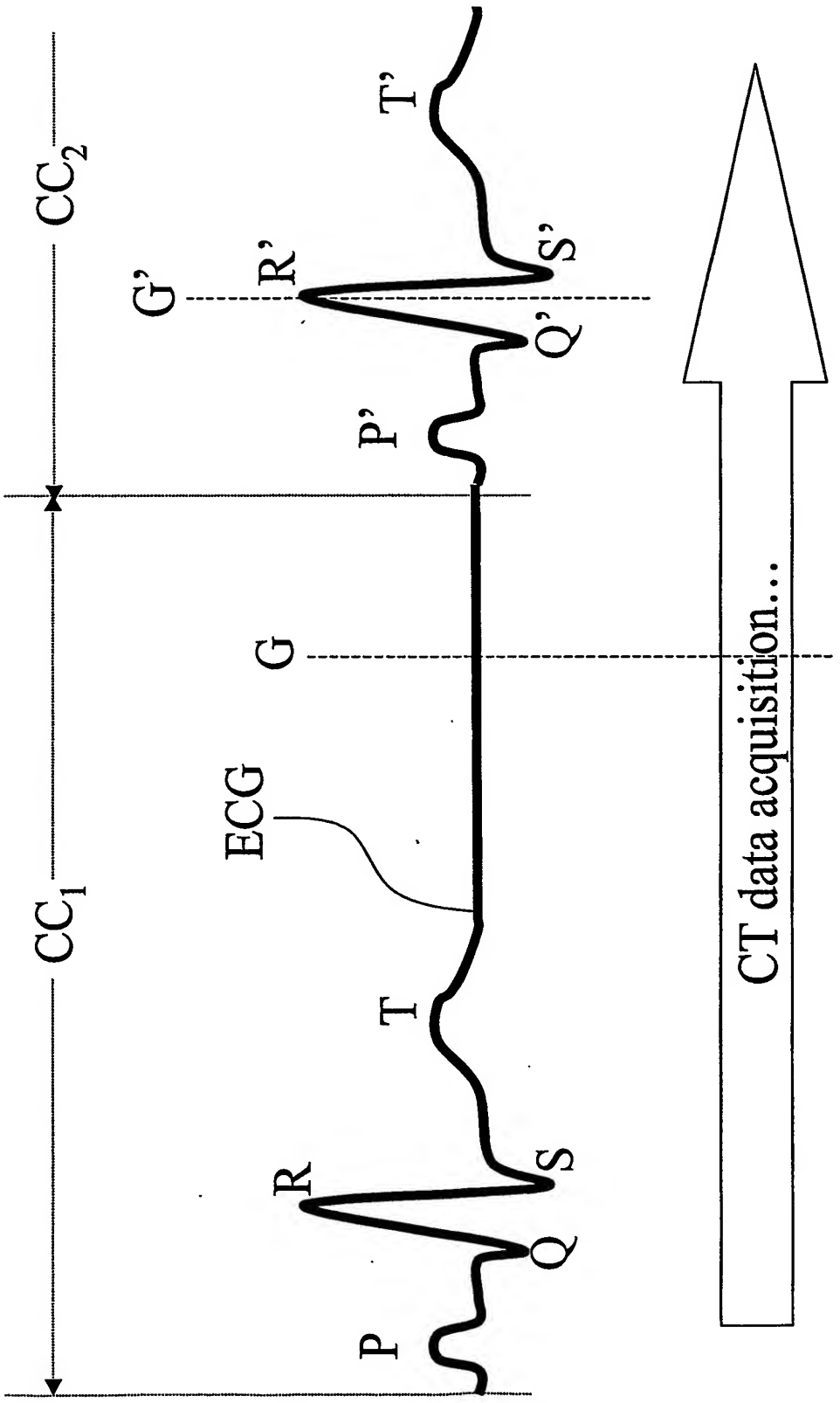


FIG 7

INTERNATIONAL SEARCH REPORT

Inte ›nal Application No
PCT/US 02/37159

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G06T11/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G06T

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category ˘	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 01 26055 A (BRUIJNS JOHANNES ;KONINKL PHILIPS ELECTRONICS NV (NL)) 12 April 2001 (2001-04-12) abstract; claims 1,2,5	1-3,5,7, 8,15,16, 18
A	page 1, line 1-16 page 2, line 31-33 page 3, line 13-29 page 4, line 6-18 page 5, line 31 -page 6, line 26	4,6, 9-14,17, 19-21

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 March 2003	04/04/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Casteller, M

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Inte nal Application No
PCT/US 02/37159

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	WO 01 37219 A (GEN ELECTRIC) 25 May 2001 (2001-05-25) abstract; claims 9-12	1-3,5,7, 8,15,16, 18
A	page 3, line 11-21 page 8, line 12-28 page 9, line 14-23 page 11, line 20-29 page 12, line 10-19 page 13, line 6-23 page 14, line 23-28 page 15, line 5-7,19 -page 16, line 26	4,6, 9-14,17, 19-21
A	EP 1 087 337 A (GE MEDICAL SYST SA) 28 March 2001 (2001-03-28) abstract; claim 1 paragraphs '0017!,'0018!,'0020!-'0025!	1-21
A	FR 2 622 991 A (THOMSON RECH) 12 May 1989 (1989-05-12) abstract; claims 1,2 page 1, line 7-10 page 4, line 5-25 page 5, line 1-14 page 6, line 3-23	1-21
A	US 5 699 799 A (XU BEILEI ET AL) 23 December 1997 (1997-12-23) abstract; claims 1-5 column 3, line 31-41 column 4, line 11-47 column 5, line 31-38	1-21
A	QIAN HUANG ET AL: "Model-based automatic recognition of blood vessels from MR images and its 3D visualization" PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON IMAGE PROCESSING (ICIP) AUSTIN, NOV. 13 - 16, 1994, LOS ALAMITOS, IEEE COMP. SOC. PRESS, US, vol. 3 CONF. 1, 13 November 1994 (1994-11-13), pages 691-695, XP010146376 ISBN: 0-8186-6952-7 abstract page 693, paragraphs 3.2,3.3	1-21

INTERNATIONAL SEARCH REPORT

information on patent family members

Int[illegible]nal Application No
PCT/US 02/37159

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 0126055 A	12-04-2001	WO 0126055 A2	12-04-2001
WO 0137219 A	25-05-2001	DE 10083899 T0	07-03-2002
		WO 0137219 A1	25-05-2001
		US 6522712 B1	18-02-2003
		EP 1277175 A1	22-01-2003
		WO 0180184 A1	25-10-2001
		WO 0180185 A1	25-10-2001
EP 1087337 A	28-03-2001	FR 2799029 A1	30-03-2001
		EP 1087337 A1	28-03-2001
		JP 2001148005 A	29-05-2001
FR 2622991 A	12-05-1989	FR 2622991 A1	12-05-1989
US 5699799 A	23-12-1997	NONE	

THIS PAGE BLANK (USPTO)